Cluster Based Hybrid Routing Protocol for Routing Streams in Zigbee Networks

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***Abstract*—Designing efficient routing protocols in Wireless Sensor Networks is a major and an active area of research. The constraints for these protocols are more strict as compared to the general wireless networking protocols due to low computation capabilities and limited energy associated with sensor nodes. Zigbee is emerging as the popular standard for wireless networks to meet the requirements of low power and low cost. However efficient for data collection and direct addressing, zigbee routing inherently doesnt offer data driven routing techniques which are important for query based WSN applications. Also to implement any standard protocol over any real hardware one requires the use of microprocessing units to do the computation related to routing at each node which adds to the cost. In this paper, we propose the design of a cost effective hybrid routing protocol over zigbee which combines continuous data delivery with data centric routing approach keeping in mind the implementation of the protocol on real hardware (Xbee RF modules).**

I. Introduction

Wireless networking is the technique of establishing and utilizing remote communications for specific purposes. Wireless sensor networks are a special type of ad-hoc wireless networks in which a large number of spatially connected, autonomous nodes are deployed to sense and monitor the environment. These combine the characteristics of being inexpensive, low-power, multipurpose sensors that are small in size and communicate untethered in short distances. WSN technology has enhanced our control on monitoring and exploring in several physical world scenarios. Owing to the fascinated utilities, it has lately become an active area of research and there have been major advancements in the fields of wireless sensors till date. Various efforts have been made to meet the challenges in the design and deployment of WSNs, localization, synchronization, data aggregation, dissemination, querying, architecture, middleware, and efficient power consumption [3]. Henceforth building applications in WSN had raised the need of a standard of a low cost, energy-effective, reliable and scalable wireless networks. Zigbee networks developed by Zigbee alliance [15], thus emerged into this domain to meet the requirements of efficient networks at significantly low costs. Today one can find applications of all sorts (home automation to commercial) built using zigbee networks. A hybrid routing protocol combining heirarchical routing approach with data centric approach has been proposed in this paper which is built on the top of zigbee on the lines of APTEEN [11]. This paper also talks about the hardware implementation of this protocol over XBee modules [16].

II. Motivation

Though zigbee routing protocol is independently efficient for data collection where every node in the network needs to send the data directly to a base station, it is not inherently an energy efficient protocol and can be improved to perform efficiently. But the problem lies in the implementation of these protocols over zigbee compliant chips. One needs microprocessing units in addition to zigbee radio modules to do some computation related to the routing protocol at every node and hence increase to the cost. Also, for the application requirements it becomes important to address the nodes of a network in such a way that the application doesnt need to care about network addresses while making queries. There is an option available to customise the firmware and modify the zigbee routing and extend the operability of the hardware in the hardware itself. In addition to inconvenience brought in while creating your own firmware, this method is not suitably well documented and could be too tedious to handle bugs in the functioning. In this paper, we propose Cluster Based Hybrid Routing Protocol for Routing Streams in Zigbee Networks (CHRS). CHRS operates over the top of zigbee exploiting the efficiency of direct addressing to send messages. It helps control the number of microprocessing units required in the network by making it application dependent and leave the computational overheads to predefined nodes (determined by the application developer). While CHRS improves zigbee by combining heirarchical routing approach to increase energy efficiency with the data centric approach to provide a platform for query based routing, it requires absolutely no additional functioning requirements from the rest of the nodes in the network. We cover the implementation details of this protocol over one of the cheapest zigbee compliant Xbee modules [16].

III. Overview

In the following sections, we first give a background of routing protocols and heirarchical routing algorithms in wireless sensor networks followed by the past work on the extension and improvement of zigbee. We then provide an introduction of the zigbee networks and zigbee compliant xbee modules. We then cover the details of the Cluster Based Hybrid Routing

Protocol for Routing Streams in Zigbee Networks (CHRS). Finally we end with the future plans towards validating this protocol.

IV. Background and Related Work

A. Routing protocols

Routing is an active area of research in sensor networks. Huge number of recent techniques and results have been proposed. Various well known routing protocols cited in almost every survey on routing protocols for WSNs are Sensor Protocols for Information via negotiation (SPIN)[13], Rumor Routing, Direct Diffusion, Low Energy Adaptive Cluster Hierarchy (LEACH) [10], Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [8], Geographic and Energy Aware Routing (GEAR) [43], Sequential Assignment Routing and others. All routing protocols can be classified [14] over these major categories -

Data Centric Routing - Demand based routing alongwith naming data to exploit data redundancy,

Location Based Routing - Use location based information to transmit the data to the destination,

Hierarchical Routing - Cluster the nodes to introduce data aggregation methods to reduce the traffic and energy consumption and

Multipath Routing - Construct several paths between the same nodes to handle link failure or to handle intensive traffic conditions.

As for the purpose of this project, we are focussing on heirarchical protocols for their specific advantage to the issues posed later. Extensive research again has been done on exploiting characteristics of heirarchical routing. Some of them are mentioned in the section below.

B. Hierarchical Routing Algorithms

- *Low-energy adaptive clustering hierarchy (LEACH)* The idea [10] is to form clusters of the sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. This saves energy since the transmissions will only be done by such cluster heads rather than all sensor nodes. Optimal number of cluster heads is estimated to be 5% of the total number of nodes.
  - Due to dynamic clustering, lifetime of the system is increased. But it also incurs extra overhead due to its dynamic nature of clustering.
  - Requires no global knowledge of the network.
  - It is a single hop routing protocol. So it is not applicable to networks deployed in large regions.
- *Power-efficient GAthering in Sensor Information Systems (PEGASIS)* PEGASIS [9] forms chains of sensor nodes such that each node transmits and receives from a neighbor and only one node is selected from the chain to transmit to the base station (sink). The data moves from node to node, aggregated and eventually delivered to the base station.
  - Uses multi-hop routing by forming chains and selecting only one node to transmit data to base.
  - Introduces excessive delay for distant nodes.
  - Concept of one leader can become a bottleneck.
  - Due to one leader, data gathering from chain can cause delays. This can be solved by the use of Hierarchical-PEGASIS [10].
- *Threshold sensitive Energy Efficient sensor Network protocol (TEEN)* It ([8]) is a hierarchical protocol designed to be responsive to sudden changes in the sensed attributes. TEEN combines hierarchical approach with the data-centric approach. The sensor network architecture is based on a hierarchical grouping where closer nodes form clusters and this process goes on the second level until base station (sink) is reached. It is shown in the figure-1.
  - This type of sensor network is responsive to sudden changes in the sensed attributes. So the no of transmissions is reduced.
  - Further can be integrated into APTEEN [11] for both responsive and periodic reports.

C. Improvement and Extensions of Zigbee Routing

There has been a little work done over the improvement of Zigbee ([19],[17],[18]). To our knowledge, none of these were actual extensions over the top of zigbee but were improvements of the routing algorithm in terms of end to end delays. [19] talks about improvement in terms of reliability, sustainability and cost reduction in terms of routing overhead but nothing about energy consumption. [18] proposes a heirarchical tree routing but could not achieve greater energy efficiency.

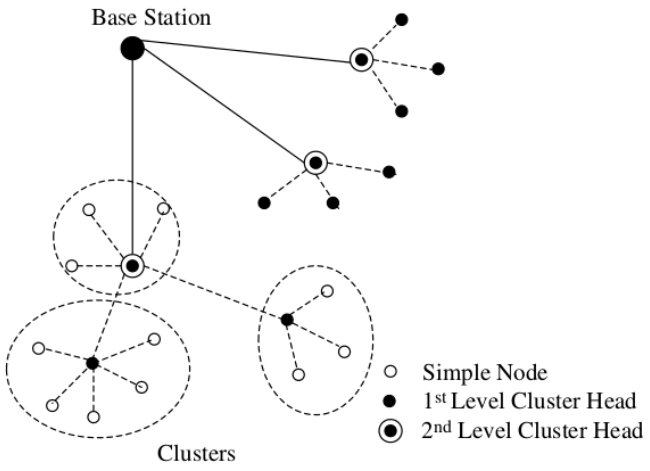

Fig. 1. Hierarchical clustering in TEEN and APTEEN

V. Introduction to Zigbee under XBee modules

ZigBee / ZigBee Pro are mesh networking protocols build on the IEEE 802.15.4 MAC/PHY. Its an open global standard. Zigbee supports advance mesh routing capabilities by defining a network layer above the IEEE 802.15.4 layers. In our case this Zigbee firmware is loaded upon XBEE/XBEE-PRO light-weight radio modules by Digi International. XBEE-PRO ZB has 11 digital I/O pins and 4 analog I/O pins with 40 meters of indoor and 120 meters of outdoor range with 2.4 GHz of frequency. Various types of sensors can be connected to the XBEE board using I/O pin and a sensor-net can be deployed in fairly large area. With Zigbee these devices can be configured as three types of devices.

- Coordinator- *Selects the channel and PAN-ID to starts a network, allow end points and routers to join the network. It assists in routing message and can store RF data for end devices. It can't go to sleep, should always remain powered.*
- Router-*It must first join a network in order to transmit, receive and route data. Same as coordinator it can allow other routers and end devices to the network and can store data for end devices. It should also remain powered.*
- End device- *Low performance and power efficient devices to collect sensory data periodically. Attain sleep mode to consume less power. It must first join the network in order to transmit or receive data.*

This type of role division makes the Zigbee sensor networks more power efficient and helps to use the same hardware as a high end coordinator device or low end remote device. To differentiate between devices Zigbee has a dual layer addressing scheme, a 64-bit permanent address and a 16-bit address which is given by the parent device at the time of joining the network. Zigbee is developed in such a way that it can handle the addressing issues of mobile-nodes in the sensor-net. The ZigBee stack consists of several layers including the PHY, MAC, Network, Application Support Sublayer (APS), and ZigBee Device Objects (ZDO) layers. The network layer uses *AODV (Ad-hoc On-demand Distance Vector)* as default routing protocol. It also supports *many-to-one*, *source-routing* alongwith network broadcast and unicast.

- Many-to-one Routing - *This routing protocol is used to determine the route till a data collector on every router. Instead of devices broadcasting route discovery messages to the data collector, the collector itself broadcasts a route request message. When a device gets this message, it chooses the optimal path through which the message arrived it and saves the reverse path in its many-to-one routing table for the collector.*
- Source Routing - *When a data collector has to send messages to the devices, then instead of performing route discovery for every device, it causes the other devices to send route-record transmission along the many-to-one route using a many-to-one routing broadcast. This route-record transmission records 16-bit address of each hop in the route. The data collector stores the routes to all the devices.*

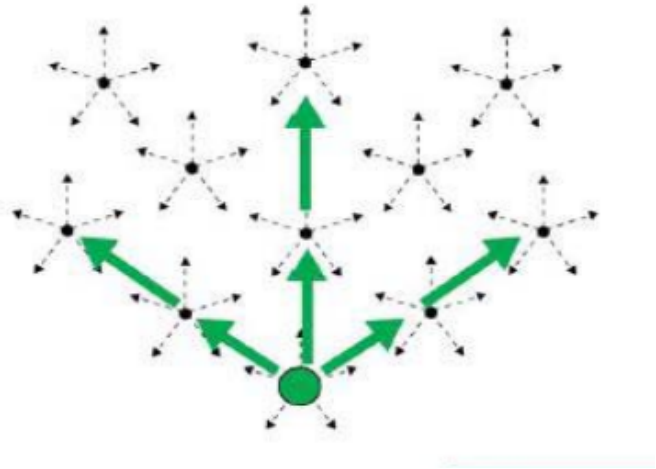

Fig. 2. Many-to-one Routing [15]

Zigbee also provides a network security mechanism. It supports three security modes residential, standard, and high security. On the network layer, network key is used to encrypt the APS layer and application data.

VI. Initial Hardware Testing and Setup

We initiated the project by setting up a wireless sensor network of PIR motion sensors[4] as an initial task. We used Xbee devices [16] for radio communication and data dissemination. We built a primitive application for testing the successful setup of a zigbee WSN.

VII. Routing Protocol

In this section we introduce our hybrid routing protocol (CHRS) built over the top of zigbee. The protocol is hybrid in the sense that it makes use of both heirarchical routing approach as well as data centric approach for routing.

A. Network Formation

In the setup, we have a coordinator deployed at the base station configured to a predefined network ID. All the rest of the sensor nodes are then configured as router or end device and deployed to desired locations. The routers and the end points are also configured to the same network ID as the coordinator as the base station so that we have one single network formed. Its worthwhile to mention here that only those nodes that have been configured as router (and the coordinator) would be able to act as group representatives as the purpose of group representative is to perform data aggregation/reduction to the received data and forward it to the base station.

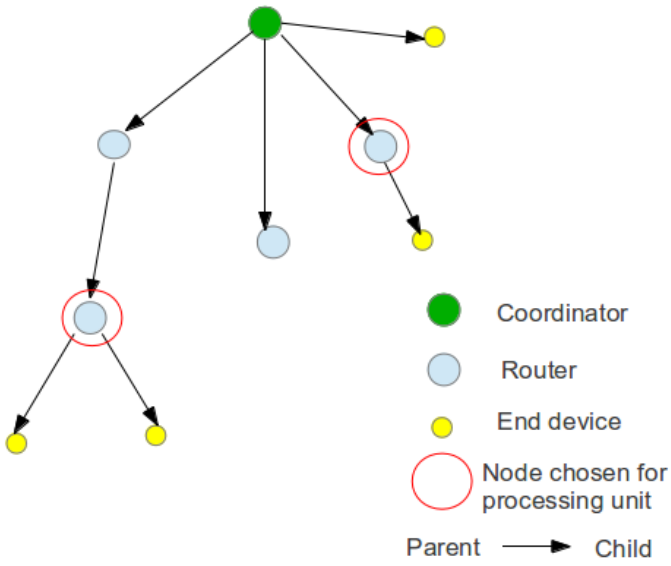

Fig. 3. A Zigbee network with parent-child associations at the time of network creation

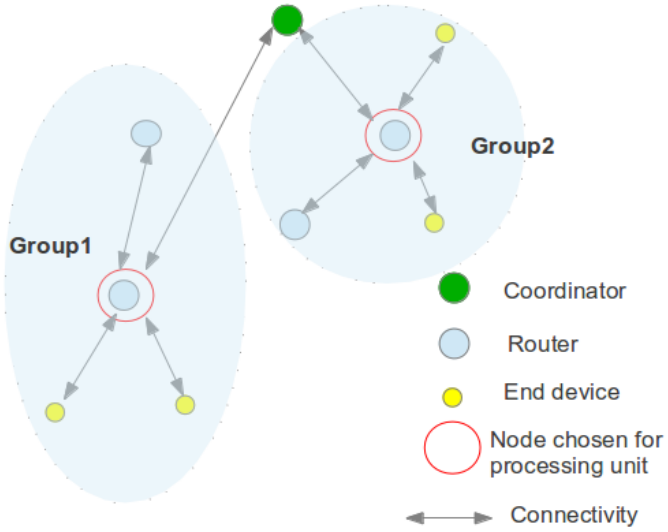

Fig. 4. The Zigbee network after the group formation. Only the functional nodes (node with processing units) are connected to the coordinator, rest communicate with the coordinator through the functional nodes.

B. Group Formation

Since in zigbee, each node is by default has the destination address set to 0 i.e. coordinator. The coordinator would at first get the data from all the nodes. The coordinator sits at the base station with the information of the application and hence about the role of each node to whether act as a ***functional node*** (node with processing units) or as a pure zigbee node. The coordinator keeps this information in the form of application level IDs (and not their network addresses to make an end user not care about it). Each *functional node* now is to act as a group reprsentative. So all we need to do is form groups for each group representative. This is done using the many-to-one routing [16] provided by zigbee in the following way:

- Each group representative behaves like a data collector and issues a many to one broadcast transmission to all the devices for many-to-one routing.
- All the route record frames received by the collectors from the devices of the network (the response to many-to-one broadcast) are then passed on to the coordinator.
- The coordinator uses the route record frames to decide the best collector for each device in the network and forms groups of network addresses corresponding to each collector.
- The corresponding groups are then conveyed to each of the collector where they are stored for future use.

Note that since many-to-one routing is issued by every collector, all the devices in the network now have an optimal route to the collectors. We now establish that how do we achieve both heirarchical and data centric character of the protocol. Before that we need to explain how the nodes of the network are addressed at the application level.

C. Application Level Addressing

An application needs to address the nodes of network for directing queries. Although one can provide unique application level IDs to the nodes of the network at the time of network initialization and keep a mapping information in the baseStation, we need a methodology to route the messages using application layer addresses. After the initialization each *functional node* knows its application level ID . The query messages are not directly passed to the intended nodes (zigbee unicast) but to the collectors . The collectors then make necessary action required to handle the queries.

D. Heirarchical character of the network

For incorporating a heirarchical approach, we have groups of nodes in the network with representatives for each group which can perform data aggregation and reduction to reduce the traffic as well as conserve energy. However, if the protocol fixes and predefines the group formation and keeps the roles of certain nodes in the structute rathenr than in the application, it becomes inconvenient for the application developer as he has to shape his applications according to the location and the functioning of group representatives. Hence, application developer should have control over deciding the allocation of role of group representatives as well as to what total number of group representatives are to be set. This control is provided at the application level where the developer specifies application level IDs of the nodes which should act as collectors. The coordinator then sends the message to these IDs informing about their role as collector and calls for initiating the many-to-one routing broadcast.

E. Data Centric aspect and Query handling

The query handling aspect is the most important aspect of a WSN architecture. Its the queries which help monitoring and control of a network. Queries are made to the network using the application level IDs and can be of the form :

1) What is the average temperature of nodes 1, 21 and 32?
2) What is the current temperature of the node 12?
3) Report the max temperature of nodes 2-8 today.
4) What nodes had temperature $>$ 40C in the previous hour?

We can classify the queries on the basis of the functioning required and the query handling process:

- **History Based Queries :** Queries requiring computation to be done over a certain long period of time fall under this class. For e.g. 4) above is history based query. These queries can be handled at the baseStation itself. As all the sensed data is sent to the baseStation by the collectors, the baseStation can keep a storehouse to respond queries which require data ranging over a long period of time. Certainly one cant expect all the historical data to be stored in the non functional nodes or even the functional nodes as they are just zigbee nodes assisted with microprocessors with limited storage. Hence its optimal to handle these queries at the baseStation. However, in such a scenario the baseStation becomes a single point of failure.
- **Emergent Queries :** These queries require immediate action to be taken. For e.g. 2) is an emergent query. Since only the functional nodes can progammably respond to the messages, these queries cant be directed to pure zigbee nodes. Since the query type is dependent upon the application, the nodes are preprogrammed to recognise query type from the message format and respond accordingly. However if the query is meant for a non-functional node, it can only be responded in the time interval governed by the *IO sampling rate*. In that case, the collector first recognises the destination of the query and decides whether it falls under its group. If yes, then it waits for the next sample sent by the destination node and forwards the data to the coordinator [1]
- **Aggregate Queries :** These are the queries which require a collective information on a certain group of nodes. For e.g. 1) and 3) are the aggregate queries. These queries need to be seperately identified by the collectors so that they can perform the aggregation operation on the collected data before sending it to coordinator and thus reduce unnecessary messages.

VIII. Efficiency Analysis

In this section we analyse what advantages the new protocol provides over original zigbee networks. We talk in terms of the below attributes:

[1]Can be made a non blocking wait if message reception acts as an interrupt.

A. Scalability

A zigbee network is itself highly scalable and its ad-hoc network join occurs automatically where a new node gets attached to the network automatically as it gets assigned a network address. In CHRS, what additionally we need for a node to join a network is to allot it a group. Any new node that is to join the network is set with the default destination address i.e. the coordinator. So whenever a new node gets attached to the network, a coordinator would be the first to recognise it in our protocol. To assign a collector to it, coordinator then sends a API frame know the parent of this new node. It then assigns it a collector same as its parent. This is exactly what is desired in terms of energy efficiency as a node attaches to the network through its parent and hence is closest to it and thus should be assigned a collector same as its parent. So a pure zigbee node can be attached to a group without much overhead to that in zigbee.

B. Energy Consumption

In CHRS, a route to the coordinator is forcibly made to pass through a group collector. Group collectors act like the cluster heads of a network and introduce a heirarchical approach to routing. We let the decision of making a node as collector and the number of collectors in the hands of the application developer. If the developer choses bad collectors which are remote to the nodes and to the baseStation, its equivalent to an inefficient cluster head and thus increases energy costs. But what is done is that it leaves the energy and application utility tradeoff to the developer himself. One can always choose collectors to minimise the energy consumption or choose collectors according to instead maximizing application utility.

C. Network Setup Costs

Network Setup costs also now become a parameter to the protocol. Choosing large number of *functional nodes* would increase the operability of the network but at the same time increase the cost.

IX. Conclusion

In this paper we introduced a protocol CHRS which is a hybrid protocol combining heirarchical approach with the data centric approach of routing. However almost all efficient routing protocols which provide data centric routing need some functionality at every node as the computations done are too intensive to be handled by pure zigbee nodes and hence require a large number of functional nodes to be implemented. In our case though, the query handling feature is provided alongwith the energy conserving heirarchical approach by keeping the number of functional nodes flexible and dependent on the end user. Although the large scale implementations of this protocol are not studied but still it gives a good cost effective, energy efficient and application friendly approach to routing.

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